Overview of Findings from ONR/DARPA N000149810747

Computational Neuromechanics: Programming Work in Biological Systems

And

Overview of Findings from

DARPA/SPAWAR N66001-00-C-8026

RHex: The CNM Hexapod

Most legged animals whose running has been studied exhibit mass center trajectories closely resembling those of a pogo-stick(Full and Farley 1999). Over the course of our five year DARPA/ ONR/SPAWAR sponsored project in Computational Neuromechanics and its application to robotics, we have begun to answer the questions, how, why, and when, in a mathematically rigorous and biologically testable manner. Addressing these simple questions has simultaneously helped advance animal motion science as well as accelerated progress in the design and control of useful legged robots.

From this research effort, numerous publications have appeared in peer-reviewed journals, books, conference proceedings and technical archives. Delivered with this summary overview of the work performed under these programs is a DVD of all archived publications, technical presentations, quarterly reports and scientific posters.

How?

In our view, the pogo stick exemplifies a general approach to solving Bernstein's "degrees of freedom" problem (Bernstein 1967) by representing in as few as possible degrees of freedom the task of translating the body's mass center. It serves as a *template* around which is stabilized (Full, Kubow et al. 2002) the body's high degree of freedom *anchor* (Full and Koditschek 1999). One way to anchor a template is via joint level and body feedback together with a careful model of the body's mechanics to achieve an attracting invariant subamanifold whose restriction dynamics is a copy of the template (Saranli, Schwind et al. 1998; Nakanishi, Fukuda et al. 2000; Westervelt, Grizzle et al. 2003). However, animal runners may not possess sufficient neural bandwidth to realize such controls at the rate required for stability (Jindrich and Full 2002; Full, Kubow et al. 2003). Indeed, it is a fact that our hexapedal running machine, RHex (Saranli, Buehler et al. 2001) anchors the same pogo stick template with absolutely no sensory information about its body states or joint loci (Altendorfer, Moore et al. 2001). Thus, for RHex and the fastest animal runners, the "how" questions may be more sharply articulated as: (i) how is the template anchored, via *preflex* (Brown and Loeb 2000); and (ii) once anchored, how is the template stabilized?

The first of these restatements remains quite elusive, and we have only begun to address in very low degree of freedom settings (Komsuoglu and Koditschek 2000) the question of how an open loop periodic signal – a purely feedforward clock – might excite asymptotically stable limit cycles in a passive mechanism, much less anchor a specified template by so doing. In contrast, we have made steady progress toward elucidating the second. Inspired by the novel biological hypothesis of self stability (Kubow and Full 1999), we proved

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	2004	

4. TITLE AND SUBTITLE
Computational Neuromechanics: Programming Work in Biological Systems
(FINAL REPORT)

5. FUNDING NUMBERS
ONR/DARPA N000149810747

6. AUTHOR(S)
Daniel E. Koditschek

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

The Regents of The Univ, of Michigan
DRDA
3000 South State Street
Ann Arbor, Michigan 48109

8. PERFORMING ORGANIZATION REPORT NUMBER
PG # C080469

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 Words)

Most legged animals whose running has been studied exhibit mass center trajectories closely resembling those of a pogo-stick(Full and Farley 1999). Over the course of our five year DARPA/ ONR/SPAWAR sponsored project in Computational Neuromechanics and its application to robotics, we have begun to answer the questions, how, why, and when, in a mathematically rigorous and biologically testable manner. Addressing these simple questions has simultaneously helped advance animal motion science as well as accelerated progress in the design and control of useful legged robots.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Computational Neuromechanics	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	unclassified	unclassified	

mathematically (Schmitt and Holmes 2000) that the Lateral Leg Spring (LLS) model – a horizontal version of the pogo stick well correlated with animal data (Full, Kubow et al. 2002) – does indeed exhibit a regime wherein gait stability arises in the near absence of any feedback. Next, we developed a version of these mathematical arguments to prove that the Spring Loaded Inverted Pendulum (SLIP) – the generally accepted model of the animal runners' sagittal plane center of mass pogo stick – also enjoys an analogous self-stable regime (Ghigliazza, Altendorfer et al. 2003). Most recently, by adding a moment of inertia to the SLIP body and exploiting natural symmetry arguments, we have begun to relate this self-stable regime to the observed behavior of RHex itself (Altendorfer, Koditschek and Holmes 2003). Thus, although a still distant vision glimpsed through the daunting terrain of numerous unsolved mathematical problems, the picture begins to emerge of a day when robots like RHex can be designed, implemented, and improved by mathematical specification rather than empirical tuning or even numerical study.

Why?

There is almost surely a strongly favorable energetic consequence to pogo stick running (Cavagna and Margaria 1966; Alexander 1990; Biewener and Baudinette 1995; Biewener, Konieczynski et al. 1998; Full and Farley 1999). However, our emerging view, hearkening back to the earliest traditions of animal motor science (Bernstein 1967), is that adopting such templates has still more important benefits to the organization of the runners' otherwise overwhelmingly complex coordination and control mechanisms.

Stability is essential to the performance of terrestrial locomotion. Arthropods are often viewed as the quintessential example of a statically stable design but results from the study of six and eight-legged runners (Blickhan and Full 1987; Full, Blickhan et al.1991; Full and Tu 1990; Full and Tu 1991) provide strong evidence that dynamic stability cannot be ignored in fast, multi-legged runners that are maneuverable. Growing mechanical (Dudek and Full 2001; Dudek and Full 2002; Dudek and Full 2004) and behavioral (Jindrich and Full 2002; Full, Kubow et al. 2003) evidence suggests that rapidly running arthropods are indeed able to recruit the mechanically self stable gaits discussed above, lending further value by reducing the attentional "cost" of control.

Of course, locomotion control consists not merely in stabilization of a given gait, but in agile maneuvers that presume well organized coordination, wherein, once again, the benefits of templates are significant. Once stabilized, the template itself can be reduced to a one degree of freedom "skeleton" of relative timing given by its phase and the interrelationship of the multiple copies necessitated by the need for multiple limbs can be coordinated by comparing and regulating relative phases (Klavins and Koditschek 2002).

When?

Both clocks and mechanisms can oscillate in isolation. By their coupling, we get a more complex family of oscillatory systems that parametrizes two trade-offs in the evolution of this locomotor control architecture: the use of feedback *vs.* feedforward control strategies (the extent to which the clocks' frequencies are influenced by those of the mechanisms); and degree of centralization (the extent to which one clock's frequency is influenced by those of its neighbors'). Choosing within this two dimensional continuum of trade-offs largely determines the efficacy of a particular gait in a particular environment (Weingarten, Lopes et al. 2004; Klavins et al. 2001; Klavins and Koditschek 2002), and early experiments with RHex (Weingarten, Groff et al. 2004) suggest that each locomotion task within each variant environment has an associated preferred point of operation on this plane.

Weighing the costs and benefits of the information exchange required to realize a given architecture can be used to make specific predictions about how animals' coordination capabilities will change or even fail as internal noise (decrements in the available neural channel capacity) or external bandwidth requirements (increments in the speed and or precision of the required mechanical coordination) are varied. In the face of the highest bandwidth performance tasks, the neural communications channels may be too noisy to permit high enough feedback or synchronization gains, and the animal may be forced to operate in a decentralized and feedforward manner, where coordination is achieved through mechanical coupling, and stability is achieved by preflex. As the bandwidth requirements of the task decrease relative to the available internal neural channel capacity, higher reflex and synchronization loop gains could be tolerated, increasing the efficacy of feedback and central authority.

Against the backdrop of such considerations, we hypothesize that tasks requiring rapid response to small perturbations within reasonably well structured environments will induce operation in the decentralized feedforward regime, while tasks presenting less predictable environments with less need for absolute speed will begin to benefit from more feedback and a greater degree of centralization. Experiments with animals in "Neuromechanical Systems Biology" (NSF Press Rel 2004) resulting from a new NSF award in the cross-cutting Frontiers of Integtrative Biology Research that has its origins in this project will probe this same question in biologically relevant terms and techniques.

RHex

The potential value of dynamically stable robotic locomotion was dramatically demonstrated two decades ago in a series of breakthrough mono-, bi- and quadrupedal hopping machines (Raibert 1986). These first dynamically dexterous robots ushered in a new understanding that robot programming could be construed as managing the phase of energy expenditure in the working environment. The central importance of underactuated (i.e., there are fewer actuators than degrees of freedom and their limited power is explicitly accounted for) design for autonomous legged machines was demonstrated in the Scout class of quadrupeds (Buehler et al. 1998), which also pioneered the use of compliant sprawled posture in quadruped bounding with consequent self-stabilized roll (Papadopoulos and Buehler 2000).

By integrating the virtues of these breakthroughs with biological inspiration from dynamic legged locomotion in arthropods, we designed the hexapedal robot, RHex. RHex is the world's first autonomous legged machine capable of mobility in general terrain approaching that of an animal. RHex (Buehler, Saranli et al. 2002) exhibits unprecedented mobility over badly broken terrain (Fig. 3). Its normalized speed is at least five times greater than that of any prior autonomous legged machine (Saranli, Buehler et al. 2001). Its normalized efficiency again sets a new benchmark for autonomous legged machines, approaching that of animals (Weingarten, Lopes et al. 2004). Not coincidentally, RHex exhibits the mass center dynamics displayed by legged animals (Altendorfer, Moore et al. 2001).

The crucial new contribution RHex makes to legged locomotion lies in its ability to recruit a compliant sprawled posture (Saranli, Buehler et al. 2001) for completely open loop stable dynamic operation (Altendorfer, Koditschek and Holmes 2003). Unlike prior legged machines that operate either only quasi-statically or only dynamically, RHex exhibits both capabilities. Its six legs and elongated body allow it to stand, creep, or walk with its center of pressure well contained within a tripod (or more) of support. However, as its speed moves into the regime of one body length per second and beyond, a well tuned RHex develops

dynamic bouncing gaits (Altendorfer, Moore et al. 2001) characterized by regular periodic steady state COM motions that resist severe and even adversarial perturbations (Saranli, Buehler et al. 2001). Recently, we have reported as well the introduction of stable and efficient bipedal gaits for RHex (Neville and Buehler 2003). In view of this task open loop stability, RHex presents a compelling physical model of the biological notion that "preflex" (Brown and Loeb 2000) stabilization may represent a key advantage of sprawled posture running.

Summary of Archival Contributions

Journal Papers and Book Chapters

1998

Thomas E. Moore, Seldon B. Crary, Daniel E. Koditschek, and Todd A. Conklin. Directed Locomotion in Cockroaches: "Biobots." Acta Entomologica Slovenica, 6(2):71-78, December 1998.

1999

Devin L. Jindrich and Robert J. Full. Many-legged Maneuverability: Dynamics of Turning in Hexapods. Journal of Experimental Biology, 202:1603-1623, May 1999.

T. M. Kubow and Robert J. Full. The role of the mechanical system in control: a hypothesis of self-stabilization in hexapedal runners. Philosophical Transactions of the Royal Society of London Series B - Biological Sciences, 354:(1385) 849-861 May 1999.

Robert J. Full and Daniel E. Koditschek. Templates and Anchors: Neuromechanical Hypotheses of Legged Locomotion. Journal of Experimental Biology, 202:3325-3332, November 1999.

2000

John Schmitt and Philip Holmes. Mechanical models for insect locomotion: dynamics and stability in the horizontal plane I. Theory. Biological Cybernetics, 83:501-515, 2000.

John Schmitt and Philip Holmes. Mechanical models for insect locomotion: dynamics and stability in the horizontal plane - II. Application. Biological Cybernetics, 83:517-527, 2000.

Robert J. Full. Stability and maneuverability in sprawled posture, legged locomotion. American Zoologist (abstracts), 40(6): 1021-1022 Dec 2000. PS Version

Devin L. Jindrich and Robert J. Full. Dynamic stabilization of rapid hexapodal locomotion. American Zoologist (abstracts), 40(6): 1077 Dec 2000. PS Version

2001

D.E. Koditschek. Integrating mechanical and biological hypotheses for high performance locomotion. American Zoologist (abstracts), 40(6): 1088-1089 Dec 2000. PS Version

John Schmitt and Philip Holmes. Mechanical models for insect locomotion: stability and parameter studies. Physica D, 156:139-168, 2001.

R. Altendorfer, N. Moore, H. Komsuoglu, M. Buehler, H.B. Brown Jr., D. McMordie, U. Saranli, R. Full, D.E. Koditschek. "RHex: A Biologically Inspired Hexapod Runner," Autonomous Robots 11:207-213, 2001.

U. Saranli, M. Buehler, and D.E. Koditschek. "RHex: A Simple and Highly Mobile Hexapod Robot ," The International Journal of Robotics Research 20, no.7:616-631, 2001.

2002

U. Saranli and E. Klavins "Object-Oriented State Machines ," Embedded Systems Programming 15, no.5, May 2002.

J. Schmitt, M. Garcia, R.C. Razo, P. Holmes and R.J. Full. "Dynamics and stability of legged locomotion in the horizontal plane: A test case using insects," Biological Cybernetics, 86:343-353, 2002.

Eric Klavins, Haldun Komsuoglu, Robert Full, and Daniel E. Koditschek. "The Role of Reflexes Versus Central Pattern Generators in Dynamical Legged Locomotion," in Neurotechnology for Biomimetic Robots, MIT Press (August 2002), eds. Joseph Ayers, Joel L. Davis, and Alan Rudolph.

E. Klavins and D.E. Koditschek. "Phase Regulation of Decentralized Cyclic Robotic Systems," International Journal of Robotics Research. , 21 (3): 257-275, March 2002.

R.J. Full, T. Kubow, J. Schmitt, P. Holmes and D. Koditschek. "Quantifying dynamic stability and maneuverability in legged locomotion," Integrative and Comparative Biology, 42:149-157, 2002.

N.J. Cowan, J.D. Weingarten, and D. Koditschek. "Visual Servoing via Navigation Functions," IEEE Transactions on Robotics and Automation, 18(4):521-533, 2002.

Devin L. Jindrich and Robert J. Full. Dynamic stabilization of rapid hexapedal locomotion. Journal of Experimental Biology, 205: 2803-2823, 2002.

<u>2003</u>

D. Campbell and M. Buehler. *"Preliminary Bounding Experiments in a Dynamic Hexapod."* Experimental Robotics VIII (2003) 612-621.

R. Ghigliazza, R. Altendorfer, P. Holmes, and D.E. Koditschek. "A Simply Stabilized Running Model," SIAM Journal on Applied Dynamical Systems 2(2): 187-218, 2003.

J. Schmitt and P. Holmes. "Mechanical models for insect locomotion: active muscles and energy losses," Biological Cybernetics 89(1): 43-55, 2003.

Robert J. Full, T. Kubow, M. Garcia, W. Schwind, D. Koditschek. Can a simple neural oscillator generate rapid running in cockroaches? Integrative and Comparative Biology (abstracts), 42(6): 1232-1232 Dec 2002.

Conference Proceedings

<u>2000</u>

E. Klavins, D. E. Koditschek, and Robert W. Ghrist. "Toward the Regulation and Composition of Cyclic Behaviors," Fourth International Workshop on Algorithmic Foundations of Robotics, Dartmouth College, NH, March 2000.

U. Saranli, M. Buehler and D. E. Koditschek. "Design, Modeling and Preliminary Control of a Compliant Hexapod Robot," IEEE Int. Conf. on Robotics and Automation, San Francisco, CA, April 2000.

H. Komsuoglu and Daniel E. Koditschek. "Preliminary Analysis of a Biologically Inspired 1-DOF `Clock' Stabilized Hopper,"Proceedings of World Multiconference on Systemics, Cybernetics and Informatics (SCI2000), Orlando, USA, July 23-26, 2000, Vol IX:670-675.

H. Komsuoglu, R. Altendorfer, R. Full, U. Saranli, B. Brown, D. McMordie, E. Moore, M. Buehler, and D. Koditschek. *"Evidence for Spring Loaded Inverted Pendulum Running in a Hexapod Robot."* Int. Symp. Experimental Robotics . Honolulu, HI (Dec 2000)

M. Buehler, U. Saranli, D. Papadopoulos and D. E. Koditschek "Dynamic Locomotion with four and six-legged robots," Int. Symp. Adaptive Motion of Animals and Machines, Montreal, Canada, Aug 2000.

<u>2001</u>

E. Klavins and D. E. Koditschek. "Stability of Coupled Hybrid Oscillators," International Conference on Robotics and Automation (ICRA2001), Seoul, Korea, May 2001.

D. McMordie and M. Buehler, "Towards Pronking with a Hexapod Robot", 4th Int. Conf. on Climbing and Walking Robots, Karlsruhe, Germany, September 24 - 26, 2001.

E.Z. Moore and M. Buehler, "Stable Stair Climbing in a Simple Hexapod", 4th Int. Conf. on Climbing and Walking Robots, Karlsruhe, Germany, September 24 - 26, 2001.

H. Komsuoglu, D. McMordie, U. Saranli, N. Moore, M. Buehler, D. E. Koditschek, "Proprioception Based Behavioral Advances in Hexapod Robot", in Proceedings of the IEEE Int. Conf. on Robotics and Automation, pp 3650 - 3655, Seoul, Korea, May 21-26, 2001.

2002

R. Altendorfer, U. Saranli, H. Komsuoglu, D. E. Koditschek, B. Brown, M. Buehler, E. Moore, D.McMordie, R.J. Full, "Evidence for Spring Loaded Inverted Pendulum Running in a Hexapod Robot," in Experimental Robotics VII, pp 291-302, Springer Verlag, 2002.

H. Komsuoglu, E.W. Moore, U. Saranli, B. Brown, D. McMordie, M. Buehler, R.J. Full, D.E. Koditschek, "Dynamical Gaits and Energy Efficiency in a Hexapod Robot", IEEE Int. Conf. On Robotics and Automation 2002

U. Saranli and D.E. Koditschek, "Back Flips with a Hexapedal Robot", IEEE Int. Conf. On Robotics and Automation 2002.

E.Z. Moore, F. Grimminger, and M. Buehler, "Reliable Stair Climbing in the Simple Hexapod 'RHex'", IEEE Int. Conf. On Robotics and Automation Washington, D.C. 2002.

D.E. Koditschek, R. Altendorfer, R. Ghigliazza, and P. Holmes. "Self-stability mechanisms for sensor-cheap legged locomotion," IV. World Congress on Biomechanics, Calgary 2002.

R. Altendorfer, R. Ghigliazza, P. Holmes, and D.E. Koditschek. "Exploiting passive stability for hierarchical control," 5th International Conference on Climbing and Walking Robots, Paris 2002.

2003

N. Neville, M. Buehler. *"Towards Bipedal Running of a Six Legged Robot."* 12th Yale Workshop on Adaptive and Learning Systems, May 2003.

R. Altendorfer, D.E. Koditschek, and P. Holmes. "Towards a factored analysis of legged locomotion models," IEEE Int. Conf. On Robotics and Automation 2003, Taiwan.

D. McMordie, C. Prahacs, and M. Buehler. "Towards a dynamic actuator model for a hexapod robot," IEEE Int. Conf. On Robotics and Automation, Taiwan.

P.-C. Lin, H. Komsuoglu, and D.E. Koditschek. "A leg configuration sensory system for dynamical body state estimates in a hexapod robot," IEEE Int. Conf. On Robotics and Automation 2003, Taiwan.

G.A.D. Lopes and D.E. Koditschek. "Visual registration and navigation using planar features," IEEE Int. Conf. On Robotics and Automation 2003, Taiwan.

U. Saranli and D.E. Koditschek. "Template based control of hexapedal running," IEEE Int. Conf. On Robotics and Automation 2003, Taiwan.

D. Campbell and M. Buehler. "Stair Descent in the Simple Hexapod 'RHex'," IEEE Int. Conf. On Robotics and Automation 2003, Taiwan.

J.D. Weingarten, M. Buehler, R.E. Groff, and D.E. Koditschek. "Gait Generation and Optimization for Legged Robots," IEEE Int. Conf. On Robotics and Automation 2003, Taiwan.

Internal Publications and Technical Notes

Uluc Saranli and Martin Buehler. *Modeling and Analysis of a Spatial Compliant Hexapod*, May 1999.

Klavins, E., et al., Coordination and Control for Locomotion, in Neurotechnology for Biomimetic Robots, J. Ayers, J. Davis, and A. Rudolph, Editors. 2001, MIT: Boston, MA. p. 351-382.

U. Saranli. *"Design and Analysis of a Flipping Controller for RHex."* 2001.

References

Alexander, R. M. (1990). "Three uses for springs in legged locomotion." International Journal of Robotics Research **9**: 53-61.

Altendorfer, R., D. E. Koditschek, and P. Holmes (2003). Towards a factored analysis of legged locomotion models. IEEE Int. Conf. on Robotics and Automation: 37-44.

Altendorfer, R., N. Moore, et al. (2001). "RHex: A Biologically Inspired Hexapod Runner." Autonomous Robots **11**: 207-213.

Bernstein, N. (1967). The Co-ordination and Regulation of Movements. Oxford, Pergamon Press.

Biewener, A. and R. Baudinette (1995). "In vivo muscle force and elastic energy storage during steady-speed hopping of tammar wallabies (Macropus eugenii)." J Exp Biol **198(Pt**(9)): 1829-41.

Biewener, A. A., D. D. Konieczynski, et al. (1998). "In vivo muscle force-length behavior during steady-speed hopping in tammar wallabies." J Exp Biol **201**(Pt 11): 1681-94.

Blickhan, R. and R.J. Full (1987). Locomotion energetics of the ghost crab II. Mechanics of the center of mass during walking and running. J Exp Biol **130**: 155-174.

Brown, I. E. and G. E. Loeb (2000). A Reductionist Approach to Creating and Using Neuromusculoskeletal Models. Biomechanics and Neural Control of Posture and Movement. J. M. Winters and P. E. Crago. New York, Springer-Verlag: 148-191.

Buehler, M., et al. Scout: "A simple quadruped that walks, climbs and runs".IEEE Int. Conf. Robotics and Automation. 1998. 1701-1712.

Buehler, M., U. Saranli and D. E. Koditschek, (2002). "Single Actuator per leg Robotic Hexapod." USA, McGill University, The Regents of the University of Michigan: US Patent 6,481,513 B2.

Cavagna, G. A. and R. Margaria (1966). "Mechanics of walking." J Appl Physiol **21**(1): 271-8.

Dudek, D.M. and R.J. Full. (2001). "Leg function in running insects: resilience and impedance of legs linked to a body." American Zoologist **41**.

Dudek, D.M. and R.J. Full. (2002). "Leg function in running insects: resilience and impedance of legs linked to a body." Society for Integrative and Comparative Biology, Anaheim, CA.

Dudek, D.M. and R.J. Full. (2004). "Mechanical properties of the support tripod in running insects." Society of Integrative and Comparative Biology Annual Meeting & Exhibition Final Program and Abstracts. Jan 4-9 New Orleans, LA.

Full, R.J., R. Blickhan, and L.H. Ting. (1991). "Leg design in hexpedal runners." J Exp Biol **158**: 369-390.

Full, R. J. and C. T. Farley (1999). Musculoskeletal Dynamics in Rhythmic Systems - A Comparative Approach to Legged Locomotion. Biomechanics and Neural Control of Movement. J. M. Winters and P. E. Crago. New York, Springer-Verlag: 192-202.

Full, R. J. and D. E. Koditschek (1999). "Neuromechanical hypotheses of legged locomotion on land." Journal of Experimental Biology **202**: 3325 –3332.

Full, R. J., T. Kubow, et al. (2003). "Can a simple neural oscillator generate rapid running in cockroaches?" J of Integrative and Comparative Biology: (to appear).

Full, R. J., T. Kubow, et al. (2002). "Quantifying dynamic stability and maneuverability in legged locomotion." J of Integrative and Comparative Biology **20**(149–157).

Full, R.J. and M.S. Tu. (1990). The mechanics of six-legged runners. J Exp Biol **148**: 129-146.

Full, R.J. and M.S. Tu. (1991). Mechanics of a rapid running insect: two-, four- and six-legged locomotion. J Exp Biol **156**: 215-231.

Ghigliazza, R., R. Altendorfer, et al. (2003). "Passively stable conservative locomotion." SIAM Journal on Applied Dynamical Systems **2**(2): 187-218.

Jindrich, D. L. and R. J. Full (2002). "Dynamic stabilization of rapid hexapedal locomotion." J Exp Biol **205**(Pt 18): 2803-23.

Klavins, E., et al., (2001) "Coordination and Control for Locomotion," in *Neurotechnology for Biomimetic Robots*, J. Ayers, J. Davis, and A. Rudolph, Editors. MIT: Boston, MA. p. 351-382.

Klavins, E. and D. E. Koditschek (2002). "Phase Regulation of Decentralized Cyclic Robotic Systems." The International Journal of Robotics Research **21**(3): 257-275.

Komsuoglu, H. and D. E. Koditschek (2000). Preliminary Analysis of a Biologically Inspired 1-DOF Clock Stabilized Hopper. 4th World Multiconference on Systemics, Cybernetics and Informatics, Orlando, FL.

Kubow, T. M. and R. J. Full (1999). "The role of the mechanical system in control: A hypothesis of self-stabilization in hexapod runners." Phil. Trans. R. Soc. Lond. B **354**: 849-862.

Nakanishi, J., T. Fukuda, et al. (2000). "A Brachiating Robot Controller." IEEE Trans. Rob. Aut. **16**(2): 109-123.

Neville, N. and M. Buehler. "Towards bipedal running of a six-legged robot," Yale Workshop on Adaptive Systems. 2003. New Haven, CT.

NSF Press Release, 16 September 2004. "NSF Announces Six 'FIBR' Awards to Tackle Some of Biology's Most Challenging Questions," **NSF PR 04-122** http://www.nsf.gov/od/lpa/newsroom/pr.cfm?ni=15000000000112

Papadopoulos, D. and M. Buehler. "Stable Running in a Quadruped Robot with Compliant Legs," IEEE Int. Conf. Robotics and Automation. 2000. 444-449. San Francisco, California.

Raibert, M., *Legged Robots that Balance*. 1986, Cambridge, MA: MIT Press.

Saranli, U., M. Buehler, et al. (2001). "RHex: A simple and highly mobile hexapod robot." Int. J. Rob. Res. **20**(7): 616–631.

Saranli, U., W. J. Schwind, et al. (1998). Toward the Control of Multi-Jointed, Monoped Runner. IEEE Int. Conf. on Rob. and Aut.,, Leuven, Belgium,.

Schmitt, J. and P. Holmes (2000). "Mechanical models for insect locomotion: dynamics and stability in the horizontal plane-II. Application." Biol Cybern **83**(6): 517-27.

Weingarten, J. D., R. E. Groff, et al. (2004). Coordination for Legged Robots. IEEE Conference on Robotics, Automation and Mechatronics, Singapore.

Weingarten, J. D., G. A. D. Lopes, et al. (2004). Automated Gait Adaptation for Legged Robots. IEEE Int. Conf. Robotics and Automation. To appear.

Westervelt, E. R., J. W. Grizzle, et al. (2003). "Hybrid zero dynamics of planar biped walkers." IEEE Transactions on Automatic Control **48**: 42-56.